USING LONG ROD PENETRATION TO DETECT THE EFFECT OF FAILURE KINETICS IN CERAMICS

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Data for projectile penetration of SiC from two types of experiments were combined and analyzed in previous work. Analysis of the data suggested the presence of the so-called “failure wave” phenomenon, interpreted as the apparent increase in the strength of SiC when the penetration velocity exceeds some critical value. These data are used as the basis for the design of a new set of experiments with the objective to remove ambiguities and uncertainties that exist in the analysis and interpretation of the original data sets.

INTRODUCTION

Data from two data sets, long-rod tungsten (W) projectiles and copper (Cu) shaped-charge jets into silicon carbide (SiC) targets, were combined to examine the penetration resistance of SiC as a function of penetration velocity [1-2]. Analysis of the data suggested that there is an increase in the strength of the SiC above some threshold penetration velocity. Penetration velocity versus impact velocity is shown for the two data sets in Fig. 1. Also shown in Fig. 1 are the hydrodynamic limits for both W and Cu into SiC, where u_{hydro} is given by:

$$u_{hydro} = \mathrm{v} / \left[1 + \left(\rho_t / \rho_p \right)^{1/2} \right]$$

In Eqn. (1), u is the penetration velocity, v is the impact velocity, ρ is the density, and the subscripts t and p indicate the target and projectile, respectively.

Kozhushko, *et al* [2], adjusted the penetration velocities to account for differences in penetrator and target densities, at least to first order, for the two data sets. These densities are given in Table 1. The adjusted penetration velocity is given by:

$$u_{adj} = u \left[1 + \left(\rho_t / \rho_p \right)^{1/2} \right]$$

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The results are shown in Fig. 2. It is noted that the W into SiC data are approaching the hydrodynamic limit with increasing impact velocity, but that the Cu into SiC data have the opposite trend.

TABLE 1. Experimental Properties

Experiment	ρ_p (g/cm^3)	ρ_t (g/cm^3)
Reverse Ballistic	19.2	3.22
Shaped-Charge Jet	8.9	3.0

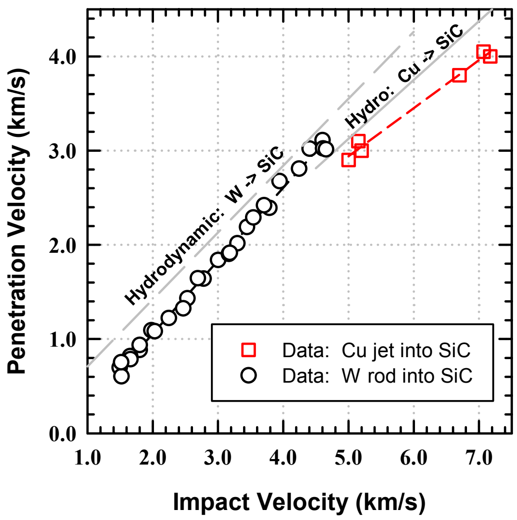

FIGURE 1. Penetration velocity vs. impact velocity.

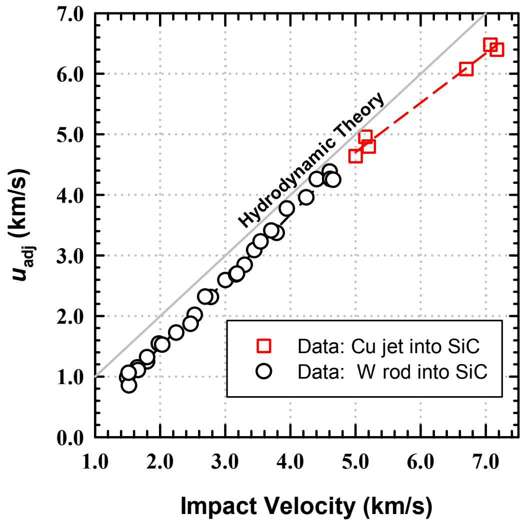

FIGURE 2. Adjusted penetration velocity vs. impact velocity.

INTERPRETATION OF EXPERIMENTAL RESULTS

There are at least four possible interpretations of these experimental results. First, the results can be interpreted as evidence of a "failure wave" in the SiC propagating at a speed of about 3.5-4.0 km/s [1-2]. Second, the results can be interpreted as reflecting the kinetics, or time dependence, associated with the failure of SiC [3]. Third, Grady has observed a phase transition in reaction-bonded SiC, due to the presence of free silica, at approximately 25 GPa [4]. Finally of course, the difference between the W-rod and Cu-jet data could be the result of important differences in the two independent sets of tests [1-3]. Each of these possible interpretations is discussed briefly below.

Evidence for a Failure Wave. Kanel, et al. [5], conducted flyer-plate impact experiments into glass. To explain the loss of strength behind the shock wave, they postulated the existence of a failure wave that propagates into the glass behind the shock front. Partom developed a numerical model for the failure wave phenomenon by assuming that the failure wave is described by the wave equation [6]. Above some threshold stress, damage is assumed to propagate at a "failure wave" velocity that is pressure dependent. Behind the failure wave, there is a two to threefold reduction in the

shear modulus. With these assumptions, Partom reasonably reproduced the wave profiles from several 1-D planar impact experiments.

For penetration, the hypothesis is that failure propagates ahead of the projectile, so that the projectile penetrates failed material. If, however, the projectile penetrates the material faster than the propagation speed of the failure wave, then the projectile must penetrate undamaged, and therefore stronger, material. In this interpretation one expects an increase in penetration resistance above some threshold penetration velocity and a consequent decrease in the slope of a penetration-velocity versus impact-velocity curve. In this context, the data in Fig. 1 can be interpreted as evidence of a failure wave propagating at a velocity between ~ 3.5 and 4.0 km/s.

Numerical simulations were conducted for the penetration of a Cu long-rod projectile into SiC, using the code CTH [7], to examine further the "failure wave" interpretation. SiC was modeled assuming a Drucker-Prager constitutive relationship, with a maximum flow stress of 3.7 GPa [8]. These results are plotted in Fig. 3, along with the data. The Cu-rod numerical result at 5 km/s lies a little below, and the 7 km/s lies a little above, the experimental Cu-jet data. Additional 7 km/s simulations were then performed in which the flow stress of SiC was increased in even multiples of 3.7 GPa. These increases in the SiC flow stress are intended to reflect the hypothesized increase in target strength when the penetration velocity exceeds the "failure wave" velocity. The three results are shown as 2X (7.4 GPa), 3X (11.1 GPa), and 5X (17.5 GPa) in Fig. 3. The numerical results parallel the Cu-jet experimental data if the strength of the SiC increases by approximately a factor of 3 between Cu-impact velocities of 5 and 7 km/s (penetration velocities of approximately 3 and 4 km/s).

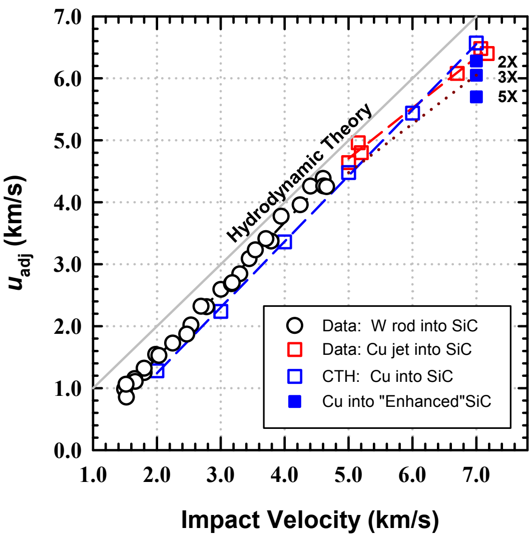

FIGURE 3. CTH simulation so a Cu rod into a model SiC material.

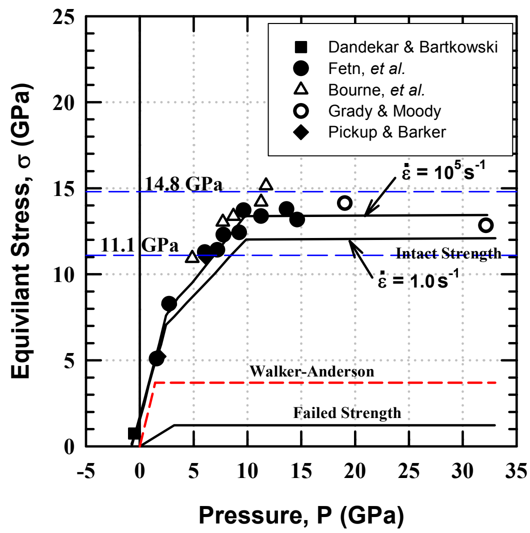

FIGURE 4. Equivalent stress vs. confining pressure for SiC (modified from Ref. [9]).

The flow stress as a function of confining pressure for SiC is shown in Fig. 4 [9] for both intact and damaged (comminuted) ceramic. The dashed curve—denoted Walker-Anderson—has a cap of 3.7 GPa, the value used for failed SiC in the CTH simulations. This flow stress has been used to reproduce very accurately the penetration-velocity versus impact-velocity data for the W-rod experiments shown in Fig. 1 [8]. The 3X and 4X values are shown as the dashed lines in Fig. 4; these lines bracket the intact strength of SiC. Thus, the simulation results are consistent with an interpretation that the projectile, above some velocity, is penetrating into undamaged, and thus stronger SiC. Unfortunately, the simulations do not inform us regarding the physics underlying this increase in target strength. A "failure wave" is one possible explanation. A second possible explanation is the kinetics of failure of SiC.

Evidence for Failure Kinetics. The kinetics of failure is an alternative interpretation of these data and simulations, as first proposed in Ref. [3]. Such an interpretation is consistent with suggestions by Grady [10]. The hypothesis is that it takes a finite amount of time for material to undergo failure. If the projectile is penetrating with a velocity sufficiently high that full failure of the material directly in front of the projectile does not have time to occur, the material will respond as less than fully failed, and thus stronger, material.

Differences in Independent Sets of Experimental Data. The third and fourth possible explanations for the change in slope of the penetration velocity (Fig. 1) are that they reflect differences between the two independent sets of experiments. These differences are discussed in Ref. [2], and include, but are not limited to:

- The experiments used two different projectiles: a W rod and for the highest velocity experiments, a portion of a Cu jet;
- Different pedigrees of SiC (different processing and densities);
- The W-rod tests used a semi-infinite target while the Cu-jet experiments used a finite-thickness target;
- Penetration velocity is inferred in the Cu-jet experiments from arrival times at the front and back surface of the target;
- There is essentially no overlap between the independent experimental data sets.

The obvious way to resolve these issues is to extend the reverse ballistic long-rod experiments to much higher impact velocities. However, to achieve the required impact velocities, the design of the original experiments had to be changed; these changes are described in the next section.

DESIGN OF NEW EXPERIMENTS

This section documents the changes that were made in the overall experimental

design to address the issues that arise from having two independent data sets. Some of the design changes were necessary to achieve higher impact velocities. A couple of changes, while not necessary, were desirable.

Higher Impact Velocity and New Target Design. It was concluded that reverse ballistic experiments were preferable to shaped-charge jet experiments since a number of assumptions must be invoked to estimate the impact and penetration velocities of the jet. Based on the original analysis [1-2] it was concluded that impact velocities up to at least 6.5 km/s are necessary to obtain penetration velocities sufficiently high that the failure wave/kinetics of the ceramic might be revealed with confidence.

The requirement for very high impact velocities meant that the new ceramic targets had to have less mass. This required a redesign of the target to: a) remove the titanium sleeve, b) reduce the diameter and length of the ceramic, c) remove the cover plate, and d) reduce the thickness of the back plate. A series of numerical simulations was performed to determine the minimum SiC target diameter required to avoid effects of the radial boundary on penetration. These calculations showed that a ratio of ceramic diameter to rod diameter (D_c/D) ≥ 20 insured no effects of the radial boundary on the penetration velocity. The new SiC target design has a ceramic diameter of 15-20 mm (which is 20-27 projectile diameters) and a length of 40 mm [11].

New SiC Material. The previous experiments used SiC-B. It was decided to use SiC-N for the new experiments since it is a ceramic of choice for armor applications. In order to be sure that the new experiments reproduced the previous results, a number of experiments were performed with the new target design using both SiC-N and SiC-B.

New Penetrator Material and Diameter. The previous research used a W long rod of diameter (D) of 0.762 mm. The new experiments use a gold (Au) rod with D = 0.75 mm. Gold was selected for the penetrator material in order to have a very high density but very low strength penetrator. The low strength for the penetrator essentially removes effects of projectile strength from analysis of the results. Tail and nose (penetration) velocities for W and Au rods into SiC are shown in Fig. 5, for an impact velocity of 3.52 km/s. The elastic deceleration waves for gold are only ~0.7 m/s, compared to~50 m/s for tungsten. Thus, the Au rod essentially does not decelerate until the rod is consumed.

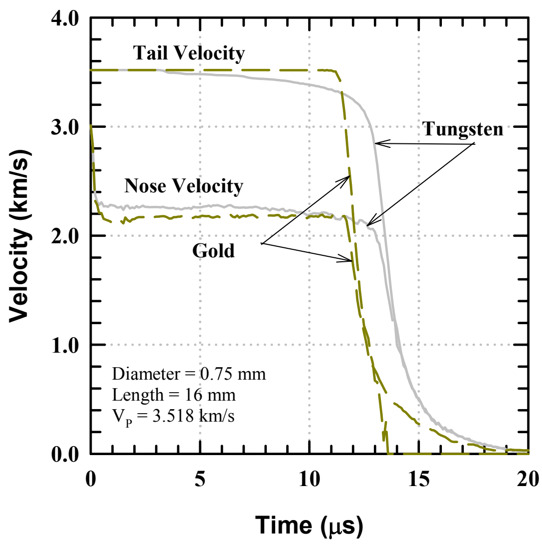

FIGURE 5. Tail and nose velocities.

Measurement Accuracy and Precision. Error analysis showed that resolving the hypothesized penetration velocity transition required higher accuracy measurements than were possible in the previous research. The improvements and procedures implemented to achieve the necessary accuracy are summarized in Ref. [11].

VALIDATION OF NEW TEST DESIGN: NEW EXPERIMENTS

With these changes in the test design, it was necessary to insure that the original data were reproduced. Initial tests successfully validated the function and precision of the flash X-ray timing and analysis procedures. Testing has now been completed to demonstrate that the changes in the experiment design described above have no unexpected effects on the penetration velocity.

Figure 6 shows the new data—the solid circles—for the Au rod into the same SiC-B target used in the original experiments, including the Ti sleeve, cover, and base plate [1-2]. Thus, these two experiments are a direct test of the effect of changing the rod material from W to Au. The new data are superimposed on the original W rod data in Fig. 6. The Au rod data are slightly lower than the W data.

The effect of the reduction in penetrator strength is shown in Fig. 7. Results of CTH calculations at eight different impact velocities for W and Au rods into SiC are superimposed on the original experimental data. The agreement between the W-rod data and the experiments is excellent. The penetration velocity for the Au rods is slightly less than that for the W rods because of the differences in the strength of the two materials (also see Fig. 5). Aside from the differences in strength, which is understood, there are no significant differences in the W-rod and Au-rod simulation results.

Also shown in Fig. 6 are data from three tests—upside down triangles—using the original SiC-B material but with a reduced diameter of 15 mm (as compared to 28 mm in the original experiments); for these tests the Ti sleeve and cover plate were also eliminated. It is evident from the results of these three tests that reducing the ceramic diameter to 15 mm and removing the Ti sleeve have no significant effects on the results. The results of these five new tests using Au rods into both the original SiC-B targets and the reduced diameter targets without Ti sleeves together with the results of the Au and W-rod numerical simulations are shown in Fig. 8; all these results are superimposed on the least-squares fit (dashed line) to the original W-rod data.

Figure 9 shows the new experimental data from tests using SiC-N as the ceramic material (upright triangles). These tests use the Au rod, the 15-mm target, and no Ti sleeve. These data are compared to the data for the same Au rod and target design but with SiC-B for the ceramic material. These new data are also superimposed on the original W rod into SiC-B data. It is concluded that changing the ceramic from SiC-B to SiC-N has no significant effect on the experimental penetration velocities.

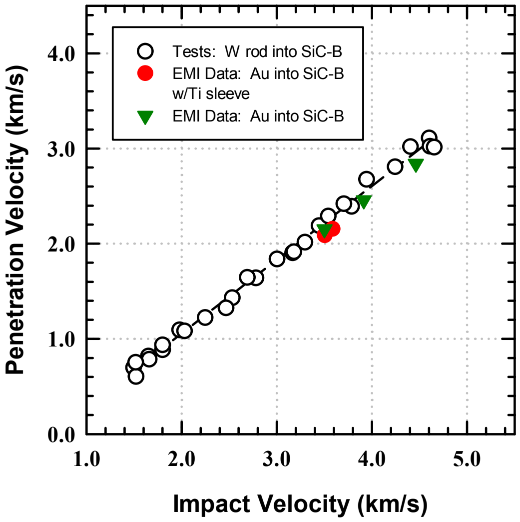

FIGURE 6. Comparison of new data to Orphal-Franzen data.

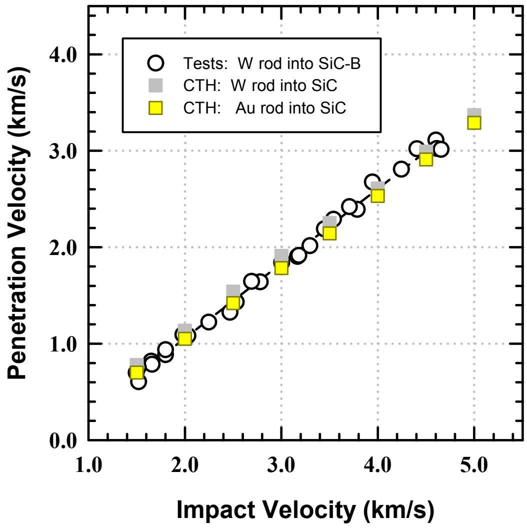

FIGURE 7. Comparison of numerical simulations to Orphal-Franzen data.

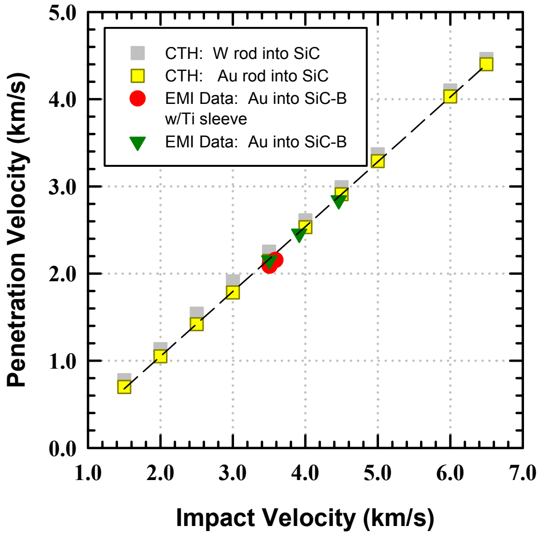

FIGURE 8. Comparison of new data with simulation results.

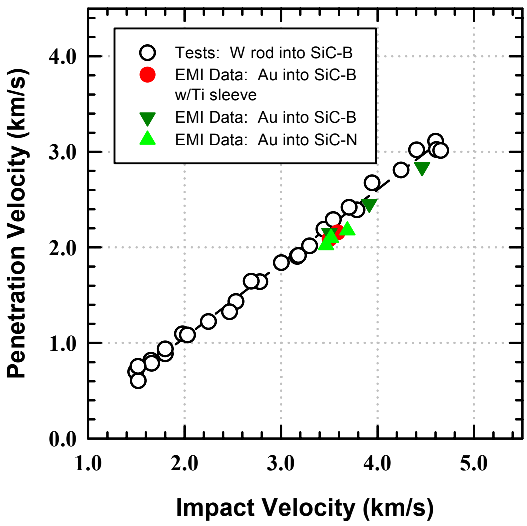

FIGURE 9. Comparison of all new data to Orphal-Franzen data.

SUMMARY

The interpretation of the combined data for W-rod and Cu-jet penetration of SiC-B reported in [1,2] was necessarily uncertain because of inherent differences in the two types of experiments. A single set of experiments is required to investigate the apparent

increase in the strength of SiC for penetration velocities greater than about 3.5 km/s. Accordingly, the W-rod experiments were redesigned to achieve impact velocities greater than about 6 km/s. The redesigned experiments necessarily use a smaller, lower mass ceramic target in order to achieve higher impact velocities. In addition, the rod material was changed from tungsten to gold to eliminate effects of penetrator strength. Finally, the ceramic was changed from SiC-B to SiC-N because SiC-N is of more current interest. The experimental and numerical simulation results reported here demonstrate that the new experimental design is successful. The new experiments give results consistent with the original W-rod experiments at impact velocities of about 3.5 to 4.5 km/s. Experiments for impact velocities up to and greater than 6 km/s are now in progress. It is hoped that these new data will help resolve the question whether the apparent increase in SiC strength for penetration velocities greater than about 3 km/s is real and, if so, what constitutes the underlying physics.

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